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Yoko-Dovyren layered dunite-troctolite-gabbro massif, North Baikal region, Russia: Structure, composition and use of mineral raw materials

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Abstract: The Yoko-Dovyren layered dunite-troctolite-gabbro massif is located in a folded frame of the South Siberian Craton (North Baikal region, Russia). The massif structure has been studied in detail in the thickest central part. The base of the section is composed of plagioclase peridotites of the endocontact, turning into the main stratigraphic sequence of five zones corresponding to changes in cumulus associations (from bottom to top): dunite → troctolite → olivine gabbro → olivine gabbro-norite → quartz gabbro-norites and pigeonite-containing gabbro. Among the mineral resources of the massif are sulfide copper-nickel ores, rocks with low-sulfide mineralization of platinum group elements and other mineralization, and chromitites. In addition, the massif contains various types of nonmetallic raw materials, including boron mineralization, diopside, and magnesium silicate rocks. These include dunites, wehrlites and troctolites, which are of high quality. They are promising for obtaining building materials (cements, concretes, asphalt concretes and building ceramics). The solution to this issue is important from the point of view of the integrated use of mineral raw materials in the development of mineral deposits, which allows for establishing environmentally safe mining works.

Key words: ultramafic-mafic complexes; Yoko-Dovyren layered dunite-troctolite-gabbro massif; sulfide copper-nickel ores; PGE mineralization; magnesium silicate rocks; building materials

俄罗斯贝加尔湖北部 Yoko-Dovyren 层状纯橄岩-橄长岩-辉长岩地块: 结构、成分以及作为矿物原材料的用途

摘要: Yoko-Dovyren 层状纯橄岩-橄长岩-辉长岩地块位于西伯利亚克拉通南部的一处褶皱构造框架中(俄罗斯贝加尔湖地区北部)。该地块的结构在其厚度最大的中部得到了着重研究。剖面底部主体成分为斜长橄长岩,并依据内部的堆晶成分变化从下往上可分为五个主要的地层序列:纯橄岩→橄长岩→橄长辉长岩→橄长辉长苏长岩→石英辉长苏长岩以及含易变辉石的辉长岩。该地块的矿化包括铜-镍矿化、低硫型富铂族元素(PGE)矿化以及铬铁矿化等。另外,该地块也含多种非金属矿物原材料,如硼矿化、透辉石、各种镁质硅酸盐岩等。它们也包括纯橄岩、异剥橄长岩和橄长岩,并以较高的品质产出,有望采掘加工成为建筑材料(水泥、混凝土、沥青混凝土和建筑陶瓷)。综合利用矿物原材料可增加矿床价值,并有助于建设环保型采矿工作体系。

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关键词: 镁铁质-超镁铁质杂岩; Yoko-Dovyren 层状纯橄岩-橄长岩-辉长岩地块; 铜镍硫化物矿; 铂族元素成矿作用; 镁硅酸盐岩石; 建筑材料

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1 Introduction

Ultramafic-mafic complexes are found everywhere. They are located in the United States of America: Duluth and Stillwater complexes (Naldrett, 2004); Canada: Voisey's Bay, Pants Lake (Naldrett, 2004), Macrae deposits in the Caldwell complex (Barrie et al., 2002); China (Lu et al., 2019), including: Bijashan (Su, 2014), Kolotonk, and several other Xinjiang intrusions (Gao et al., 2012; Mao et al., 2008; Chai et al., 2008), Baim, Taihe (Liu et al., 2014; Hou et al., 2012), Dalabute (Zhou et al., 2001); Western Australia: Permian Podong (Zhang et al., 2019), Jameson Range (Karykowski et al., 2017), Sally Malay (Sproule et al., 1999); South Africa: Tabankulu, Bushveld (Naldrett, 2004); Brazil: Brejo Seco (Salgado et al., 2016), Niquelandia (Ferreira et al., 1995); and other countries. In Russia, the complexes extend throughout the territory, starting from the Kola Peninsula (Nikolaev and Khvorov, 2003) through the Urals (Pervozhnikov, 2011; Fershtater et al., 1997), Eastern Siberia (Yurichev and Chernyshov, 2014; Cherkasova and Mazurov, 2012) and the Far East (Buchko et al., 2018; Novakov, 2017; Stepanov et al., 2008).

Ultramafic-mafic intrusions include various types of mineral deposits. Both ore and non-metallic raw materials can be extracted from them, which is of interest from the perspective of integrated development of mineral resources. The solution to this problem is shown by the example of the Yoko-Dovyren layered dunite-troctolite-gabbro massif of the North Baikal region, Russia.

2 Yoko-Dovyren massif

2.1 Location, structure and composition of the Yoko-Dovyren massif

The Yoko-Dovyren intrusion is located in a folded frame of the South Siberian Craton (Fig.1), 60 km northeast of the north tip of the Lake Bai-

kal (North Baikal region, Russia). It lies conformably with the host rocks among steeply falling igneous-carbonate-terrigenous (mainly black shale) strata of the Synnyr rift (Konnikov, 1986; Kislov, 1998; Rytsk et al., 2002).

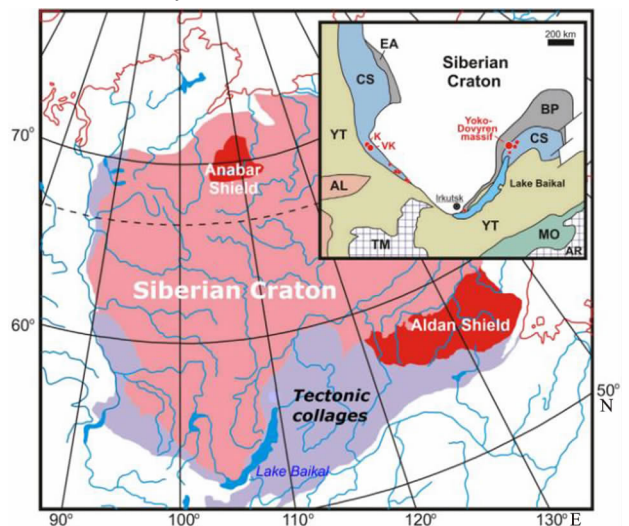


Fig.1 Major tectonic features of the Siberian Craton and its south margin (Ariskin et al., 2018). The outline of the Siberian Craton includes the Neoproterozoic and older basement. BP: 'outer' Baikal-Patom Foldbelt; EA: East Angara Fold belt. Tectonic Collages: CS: Circum-Siberia (Proterozoic); YT: Yenisey-Transbaikalia (Vendian through Early Ordovician); AL: Altay (Vendian through Ordovician); MO: Mongol-Okhotsk (Devonian through Late Jurassic). Late Proterozoic and Cambrian superterranean; AR: Argun-Idermeg; TM: Tuva-Mongolia. The Late Proterozoic intrusions of the south margin of the Siberian Craton are shown by red circles and include: K: Kingash; VK: Verkhniy (Upper) Kingash; YDM: Yoko-Dovyren massif; and other small mafic to ultramafic bodies hosting Cu-Ni-PGE deposits and sulphide ore occurrences.

The Yoko-Dovyren massif with a length of ~26 km is a part of the Synnyr-Dovyren volcano-plutonic complex. The complex also includes the underlying intrusive sheets of plagioperidotites and dikes of leucocratic gabbro-norites (Kislov, 1998; Ariskin et al., 2018); dykes in the roof and host rocks are less studied. The complex consists of the effusive formations of the Synnyr ridge overlapping these bodies (Fig.2), including high-Ti basalts of the Inyapuk suite and low-Ti andesites to basalts of the Synnyr suit (Manuilova and Zarubin, 1981). Composition data (geochemis-

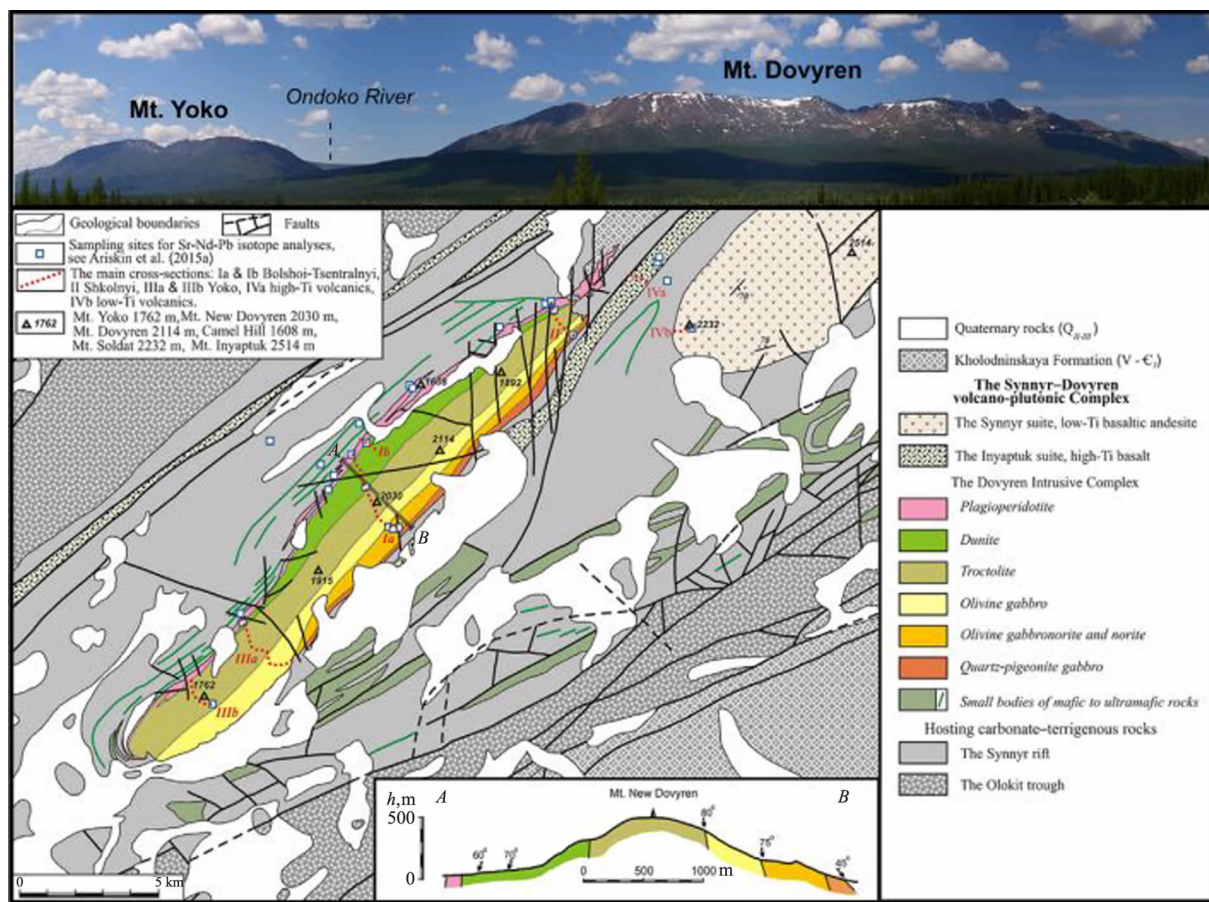


Fig.2 Photograph of the Yoko-Dovyren massif facing northwest (top) and a schematic geological map of the southwest termination of the Olokit trough (Ariskin et al., 2018).

try and isotopy) indicate the genetic relationship of the intrusive and volcanic rocks of the low-Ti series (Ariskin et al., 2015).

The age of the complex dated using zircons falls into an overlapping interval from 728.4 ± 3.4 Ma for the Yoko-Dovyren massif to 722 ± 7 Ma for the associated volcanics (Ariskin et al., 2009, 2013). U-Pb baddeleyite dating from pegmatoid gabbro-norite in the preroofed part gave 724.7 ± 2.5 Ma (Ernst et al., 2016).

As a result of tectonic movements, the Yoko-Dovyren massif has an almost vertical orientation, which allows it to be studied from the lower to upper contacts by testing surface exposures. The structure of the massif was studied in detail in the thickest central part (up to 3.5 km), in the vicinity of the Bolshoy and Tsentralny creeks (Fig.3; Kislov, 1998; Ariskin et al., 2018).

The base of the section is composed of endo-contact rocks (quenched gabbro-norites and picrodolerites; above-plagioclase lherzolites), which

turn into the main stratigraphic sequence of five zones corresponding to changes in cumulus associations (from bottom to top): dunite (Ol + Chr) → troctolite (Ol + Pl + Chr) → olivine gabbro (Pl + Ol + Cpx ± Chr) → olivine gabbro-norite (Pl + Ol + Cpx ± Opx) → quartz gabbro-norites and pigeonite-containing gabbro (Pl + Cpx ± Opx ± Pig). Here, the troctolite zone is a stratified series, including the subzones with interbedding troctolites and plagiodunites, and then troctolites and olivine gabbros. It is possible that quartz gabbro-norites of the preroofed part of the massif and pigeonite-containing gabbros belong to the additional intrusion synchronously with dikes of gabbro-norites. In this zone, gabbro-pegmatites and quartz granofirs are widespread, and the upper contact is composed of fine-grained gabbro-norites.

At the base of the Yoko-Dovyren massif, below quenched contacts, one can trace extended (up to several km) plagioperidotite intrusive sheets (Kislov, 1998). They are usually separated

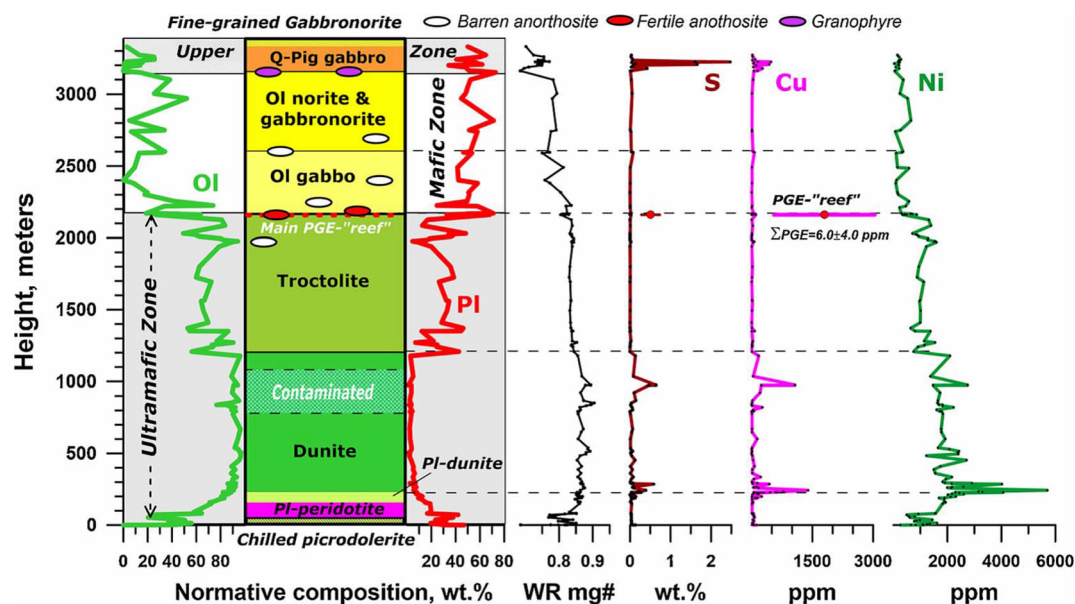


Fig.3 Internal structure of the Yoko-Dovyren massif along a typical cross-section through its central part (Ariskin et al. 2016).

from the main intrusive body by thick (up to 150–200 m) interlayers of hornfelsed host rocks. The results of geological mapping of the massif show (Fig.2) that in the central, thickest part, these extended intrusive sheets can meet with the basal base of the intrusion, probably of a somewhat deformed cone shape (Ariskin et al., 2018).

2.2 Minerals of the Yoko-Dovyren massif

2.2.1 Sulfide copper-nickel ores

Sulfide-rich rocks, down to sideronitic and massive ores, are concentrated along the entire extended lower contact - the Baikal deposit (Gurulev, 1965; Konnikov, 1986; Kislov, 1998). Mineralization was discovered in 1949. Exploration work was intensively carried out in 1959–1963, and to a smaller extent in 1976–1979 and 1986–1993.

The richest mineralization is concentrated in the plagioperidotite zone and intrusive sheets of the same composition extending from it into the bottom rocks. In plagioperidotites, disseminated and massive sulfide ores are distributed unevenly. The disseminated mineralization (Fig.4) is distributed much wider than massive one. The bodies of disseminated sulfide ores can be traced along the strike to 1400–1700 m with an emergence width of 8–25 m (in puffs up to 80 m). The orientation of the disseminated mineralization lenses, as a rule, coincides with the strike and dip of the bottom horizon of plagioperidotites. The bodies of massive ores are usually em-

bedded in areas of sulfide impregnation. Four areas of the concentration of sulfide copper-nickel mineralization are distinguished within the northwest contact of the massif.

The mineral composition of sulfide ores of the Baikal deposit is represented by the “triad”, usually for magmatic sulfide-nickel deposits: pyrrhotite, pentlandite, and chalcopyrite; oxides such as magnetite and chromite are found in lesser amounts. Pyrrhotite predominates quantitatively.

The richest ores are known at the northeast end of the massif (Ozernyi site). The area of disseminated sulfide ores can be traced along the bottom of the intrusion along the strike up to 700 m with an average thickness of 8 m. Within this zone, there is a number of veins and lenses of massive sulfide ores. The largest sulfide vein is traceable along the strike to 650 m with a thickness of 0.7–1.0 m. There are also smaller sulfide veins confined to the tectonic zones of the sublatitudinal and submeridional directions. Their thickness ranges from 0.2 to 1.5 m. Sublatitudinal veins are more extended than submeridional veins (15–50 m). According to drilling data, the veins fall almost vertically (50–70° and are found at depths of more than 500 m.

Three other sites are located in the middle part of the northwestern pluton contact, in the upper reaches of the Tsentralny and Bolshoy creeks, as well as in the estuary of the Rybachy creek. The

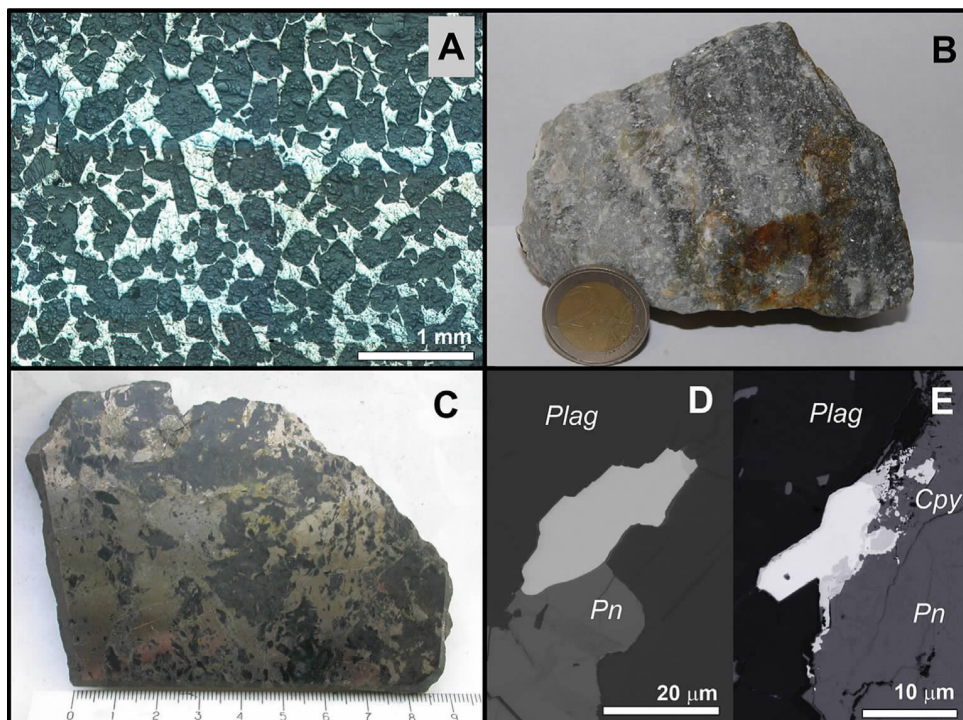


Fig.4 Sulphide mineralization of the Dovyren Intrusive Complex (Ariskin et al., 2018). A net-textured Cu-Ni sulphide ore from a sill below the Yoko-Dovyren massif (sample 07DV107-1); B; Low-mineralized PGE-rich anorthosite from the Main PGE Reef (07DV146-1); C, A; massive Po-rich sulphide ore from the Ozernyi prospect at the NE termination of the Yoko-Dovyren massif (sample provided by D.A. Orsoev); D, E; Back-scattered electron (BSE) images of Pt-Pd-Ag minerals associated with sulphides; D; Moncheite in a thin anorthositic vein (the Main PGE Reef, sample 07DV146-2); E, A; composite grain of moncheite (light) and telargpalite (grey) in a low-mineralized troctolite.

disseminated and vein-disseminated mineralization of the Tsentralny and Bolshoy creeks are localized in the lower part of the bottom plagioperidotite intrusive sheets at a certain distance from the contact. One of the zones on the Bolshoy creek extends at a distance of 1400 m with an average thickness of 4 m and can be traced by wells to a depth of 110 m. Sulfide impregnation is uneven with a content of ore minerals of up to 30%.

In the southwest part of the massif (Rybachy site), in the plagioperidotites of the bottom part and at a distance of 20–30 to 300 m from the contact there is a series of ore zones with a thickness of 1–2 to 25 meters and a sulfide content of up to 30%. In addition, in the plagioperidotite intrusive sheet, a zone of densely disseminated to massive ores with a thickness of up to 2 m can be traced to 200 m.

The disseminated ores are characterized, as a whole, by low concentrations of sulfides (5–10 vol.%), but among them there are areas of densely disseminated to net textured ores (Fig.4) with their higher contents (up to 30%). In such

areas, the concentrations of useful components reach “ore” levels (0.3–1.05 wt.% Ni). A distinctive feature of the ores of the Yoko-Dovyren massif is the high content of cobalt, which isomorphically enters into pentlandite, violarite, nickelin, and gersdorffite (up to 12% Co is found in the last two minerals), and forms independent minerals: cobaltite and cobalt mackinawite. In addition to the main components, nickel, copper, cobalt, and sulfide ores have increased concentrations of PGE (Pt-up to 0.5 ppm; Pd-up to 3.8 ppm; Rh-up to 0.24 ppm), gold (up to 0.32 ppm), silver (up to 16 ppm), selenium (up to 23 ppm), and tellurium (up to 14 ppm).

The resources of the deposit are estimated at 147 thousand tons of nickel, 51 thousand tons of copper, and 9.5 thousand tons of cobalt. By drilling to a depth of only 300 m, the deposit has not been studied enough; only one well has been drilled to 750 m.

2.2.2 Low-sulfide platinum mineralization of the Main Reef

Much later, layered horizons (“reefs”) of

rocks of the greatest petrographic heterogeneity with low sulfide mineralization of platinum group elements (PGE) were found in the Yoko-Dovyren stratified massif (Distler and Stepin, 1993; Kislov et al., 1993; Kislov and Orsoev, 1993; Orsoev et al., 1995; Kislov, 1998; Konnikov et al., 2000; Spiridonov et al., 2019a, b). The first lower and the most PGE-rich horizon is called the Main Reef or Reef I (Fig.2). It is confined to the transition site from the rhythmically stratified troctolite-olivine-gabbro series to the massive olivine-gabbro.

The Main Reef occupies a varying position from 170 to 280 m above the marker horizon of poikilitic plagiowehrlites. The Main Reef is traced by route intersections for more than 20 km along the strike and, using the terrain, to a depth of about 1 km. A characteristic feature of the Main Reef is schlieren and lenticular segregations of anorthosites (Fig.4), to a lesser extent of gabbro-pegmatites, taxitic troctolites and olivine leucogabbro-norites with a thickness from a few cm to a meter or more. Along the strike, they extend conformably with the stratification for 2–5 m, rarely 40 meters or more, forming discontinuous echelon ore zones. Often they are oriented sub-horizontally, that is, they cut across a subvertical stratified series.

In ore-bearing pegmatoid anorthosites, the size of olivine crystals is up to 6 mm, bytownite-anorthite up to 12 mm, poikilocrystals of diopside-augite up to 120 mm × 40 mm, ferruginous bronzite up to 50 mm. Thin sulfide impregnation in anorthosites gravitates to areas and bands with a noticeable amount of dark-colored minerals, which are actively replaced by sulfides. Usually sulfides are less than 1%, but their content can reach 7%. Sideronitic sulfides are represented by crystallization products of Ni-Cu-Fe-S liquid. The predominant ones are small crystals and their Mss aggregates transformed into intergrowths of troilite, Fe-pyrrhotite, and pentlandite. Small crystals of Iss1, undersaturated with sulfur, transformed into intergrowths of cubanite, troilite, pentlandite, are widespread. Less common are the more coppery Iss2, Iss3, Iss4, Iss5, and solid-state transformation products Iss5-talnakhite. Chalcopyrite, cubanite and talnakhite contain

pentlandite exsolution lamellae (Spiridonov et al., 2019a).

PGE minerals are found not only in sulfide aggregates, but also on the contact with silicates, as well as in a silicate matrix in close intergrowth with hydroxyl-containing minerals. They are mainly represented by moncheite (Fig.4), tetraferroplatinum, potarite, kotulskite, moncheite and zvyagintsevite, as well as telargpalite, insisvaite, michenerite, paolovite, sperrylite, froodite, mertieite, niggliite, atokite, sobolevskite, majakite, hessite, rustenburgite, stannopalladinite, taymyrite, heversite, palladium germanite, minerals of the gold-silver series, silver amalgam, altaite (Kislov, 1998; Ariskin et al., 2018; Spiridonov et al., 2019a, b).

The contents of precious metals in the rocks are distributed extremely unevenly. Anorthosites are most enriched, in separate samples, of which the precious metal content are: Pt-4.1, Pd-7.8 and Au-3.2 ppm. Contents of copper reach 0.7%, and nickel 0.4%. Hypothetical resources: Pt-42.4 t and Pd-66 t.

2.2.3 Other sulfide mineralization

Impregnation of sulfides was also found on other stratigraphic horizons of the massif (Fig.2); their industrial significance has not yet been established.

Low-sulfide mineralization Os-Ir-Ru with disseminated Mss-type sulfides is in the horizon of plagiodunites lying between plagiolherzolites and dunites (Ariskin et al., 2018). The disseminated mineralization of troilite and pentlandite, less often the vein-disseminated mineralization with a high content of Pd is in the upper part of the dunite zone in the areas around the after dolomite xenoliths (the Bolshoy creek, Kislov, 1998). Low-sulfide high-copper mineralization of PGE is in troctolites of the lower part of the stratified series-“Konnikov zone” (Fig.4; Ariskin et al., 2018; Ariskin et al., 2020).

Sulphide mineralization is in troctolites and vein diopsidites in the lower part of the plagiodunite-troctolite subzone in the areas around the after dolomite and after aleurolite xenoliths (the Bely creek, Kislov, 1998).

Low-sulfide mineralization is in troctolites containing cobalt pentlandite (“under trigger

point”). Low-sulfide PGE veins and schlieren of anorthosites and gabbro-pegmatites are among massive gabbros and gabbronorites (Kislov, 1998).

Horizon of relatively sulfide-rich (in places up to ~10 wt.%) olivine-free gabbronorites is within the pre-roofed zone (Kislov, 1998; Ariskin et al., 2016, 2018).

In intrusive sheet gabbronorites in the roof and bottom, sulfide mineralization is observed in gabbro-pegmatites; quartz-carbonate veins impregnate gabbronorites with quartz; and large impregnation of chalcopyrite and galena is observed in quartz-carbonate veins that do not cause silicification of gabbronorites, with sharp contacts (Kislov, 1998).

Thin pyrite-pyrrhotine impregnation prior to vein mineralization is characteristic of exocontact terrigenous rocks. In addition to pyrite, sphalerite and galenite occur in carbonate deposits (Kislov, 1998).

2.2.4 Chromitites

Wehrlites, diopsidites, chromitites were found at the zone of magnesian skarns on the left bank of Bol'shoy (Big) creek upper part. Chromitites are schlieren and vein like segregation of chromespinels most often (Fig.5).



Fig.5 Sample B1b; two chromespinel layers are parallel to magnesian skarn.

Its size is up to 0.5–1 m in length and 10–20 cm in width. Chromitites consist from 40–60% of euhedral chromespinel. Veins of massive chromitite with width up to 2–3 cm are less common. The olivine, green clinopyroxene, green or greenish-brown garnet chlorite, are typical for chromitites. The clinopyroxene and chlorite sur-

round the chromespinel grains often. The chromitites at the contaminated dunites of the Yoko-Dovyren intrusion represent the high-chromium skarn, forming at the magmatic stage. Its formation is a result of microbasalt liquid reacting with CO₂ fluid and excess calcium from dolomitic xenoliths extracted at a decarbonatization (Kislov et al., 2019).

2.2.5 Boron mineralization

Axinite-quartz veins with carbonate and pyrite with a thickness of 10–20 cm, and a series veins of 1–2 cm thickness, were found in a diabase dyke with a thickness of 7–8 m, which is exposed behind the northwest wedging of the massif. The dike is crossed by these transverse veins. Wedge-shaped crystals of axinite (the first millimeters – 1.5 cm) form brushes (sometimes with radial ray intergrowths) in the selvages of the veins. Characteristics are individual crystals, fine-grained aggregates of axinite in quartz. Crystals are characterized by rough combination striation. Axinite is transparent, clove-brown; when weathered, it becomes grayish-beige and opaque. In terms of chemical composition, it is magnesian-ferruginous axinite with a high content of magnesium and manganese. In quartz aggregates, finely scaled chlorite, acicular to elongated prismatic crystals (also in axinite), and pyrite hexahedra (almost completely replaced by iron hydroxides) are observed in quartz aggregates. Judged from the negative pseudomorphoses, calcite rhombohedra were present in the selvages of the veins (Kislov and Melyakhovetskii, 1989).

2.2.6 Blue diopside

The development site of the blue diopside - the Snezhniy site - is found at the source of the Bely creek. The mineral is found in xenolith composed of brucite marbles, and in troctolites. Xenolith is 100 m long along the strike and 10–15 m thick (Fig.6).

Diopside is developed around the lenticular and pipe-like segregations of quartz. Lime-magnesian skarn is developed around them; quartz-diopside + wollastonite + calcite-light porcelaneous monticellite + wollastonite + calcium hydrosilicates-brucite marble. On the contact with quartz, diopside is blue (Fig.7), then light green, then bright green; sometimes it happens differently (Fig.4).



Fig.6 Outcrop of blue diopside at the Yoko-Dovyren massif in 2014.



Fig.7 Sample of blue diopside. White: wollastonite; Pink: foshagite.

Wollastonite-calcite-diopside rock is usually referred to as blue diopside. Diopside forms idiomorphic isometric crystals, and wollastonite and

calcite form xenomorphic grains. Moreover, these two minerals are not as noticeable as colored diopside. The thickness of blue diopside bodies (zones, as well as lenses, veins) is usually less than 10 cm (although can be up to 0.5 m) (Kislov, 2020). Polishing is difficult due to the fact that diopside, wollastonite and calcite have different hardness and perfect cleavage. The resources of ornamental diopside are estimated at 1 thousand tons. The stone was mined illegally, used for the production of souvenirs and jewelry. The exceptionally chemically pure blue diopside is widely used as a reference for magnesium and calcium in microprobe studies.

2.2.7 Magnesium silicate rocks

The Yoko-Dovyren massif includes a huge amount of non-metallic raw materials, including magnesium silicate rocks, in particular, dunites, wehrlites, and troctolites.

Dunites of the Yoko-Dovyren massif have a panidiomorphic structure. They include 80–97% olivine ($f = 8–15\%$), up to 10% interstitial clinopyroxene ($f = 9–11\%$) and plagioclase (bytownite-anorthite), 1–2% accessory chrome spinel of two generations. Orthopyroxene and phlogopite are observed occasionally. Chrome spinel is close in composition to chrompicotite and forms crystallographically faceted inclusions in olivine or aggregates of grains in interstitia (Fig.8).

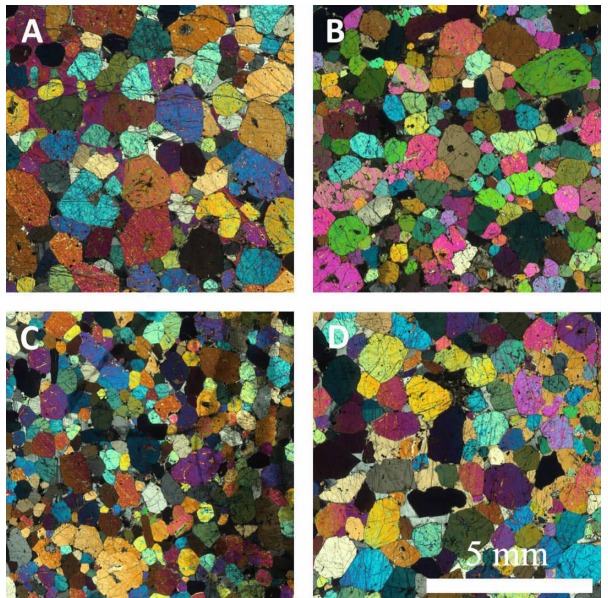


Fig.8 Photographs of samples of dunite in crossed nicols-monomineral aggregate of fresh olivine; a–09DV500-37; b–09DV500-40; c–09DV500-59; d–09DV500-82. Photo credit: S.N. Sobolev.

Fresh dunites of high quality are practically unserpentinized. Occasionally, loop serpentinization occurs and olivine is replaced by minerals of the iddingsite-bowlingite group. They do not contain hydroxyl- and alkaline-containing minerals (Kislov, 1998).

Dunites have almost constant chemical composition over the entire distribution area. Its distinctive feature is a sharp excess of the magnesium oxide over calcium oxide in the range of 15–36 times (Kislov, 1998).

In addition to fresh ones (Fig.9), dunites in the massif are also represented by disintegrated rocks (dunitic sand), identical in structure and chemical composition to the source ones. Loose rocks consist of particles of different sizes, mostly represented by olivine crystals or their fragments (Kislov, 1998).

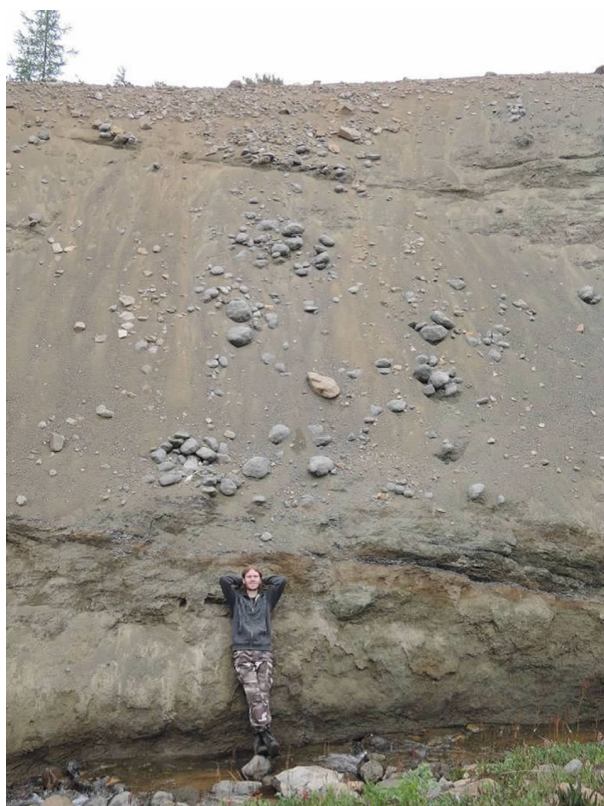


Fig.9 Exposure of fresh dunites in the bed of the Bolshoy creek, about 200–300 m above the contact. Photo credit: S.N. Sobolev.

In the dunite zone, wehrlites of two modifications are widespread. Endocontact wehrlites are characterized by various variants of structures and mineral composition. Clinopyroxene, represented by variations from diopside to fassaite ($f=8\text{--}10\%$), forms the largest idiomorphic build-

ups. They include isometric resorbed olivine grains, as well as isometric spinel crystals (black and green). Olivine, less commonly pyroxene, is serpentinized along cracks. The rocks are characterized by pockets and veins of secondary calcite. Thus, pockets of calcite and amesite are found in coarse-grained heterogeneous grain wehrlite (Kislov, 1998).

Another modification is represented by wehrlites with a poikilitic structure. Poikilitic plagiowe-hrlites consist of olivine (80–85%), plagioclase and clinopyroxene (5–10%), and alumochromite (1–2%). Clinopyroxene and plagioclase form oikocrysts (0.5–5 mm), which contain small rounded olivine grains. They are more resistant to weathering than fine-grained olivine, therefore they give plagiowe-hrlites a tuberous or acicular surface (Kislov, 1998).

The structure of troctolites is allotriomorphic-grained, the texture is massive up to trachytoid. The olivine grains in troctolite have an angular embayment shape, occasionally include small rounded idiomorphic plagioclase crystals (Kislov, 1998).

Volumes of magnesium silicate rocks of the Yoko-Dovyren massif amount to billions of tons. From the point of view of the integrated use of mineral raw materials, they need to be involved in the production turnover to obtain marketable products.

3 Use of mineral raw materials of the Yoko-Dovyren massif

Magnesium silicate rocks are a promising raw material for use in various directions (Khudyakova and Timofeeva, 2018a; Khudyakova and Timofeeva, 2019). Valuable components such as magnesium, silicon, non-ferrous metals, etc. can be isolated from them (Lazaro et al., 2012; Oelkers, 2001; Kleiv and Thornhill, 2011). They can be used as long-acting fertilizers (Makarov et al., 2003; ten Berge et al., 2012). They can be used as reagents for wastewater treatment (Kremenetskaya et al., 2010). Rocks containing magnesium silicates are able to absorb carbon dioxide therefore are promising for combating the greenhouse effect (Wang et al., 2019; Lacinska et al., 2017; Streffer et al., 2018). However, magnesi-

um silicate rocks are of most interest for the construction industry sectors, in particular, the production of building materials (Khudyakova and Timofeeva, 2018b; Khudyakova et al., 2019).

3.1 Cement production

From the economic and environmental points of view, the most advantageous is the use of magnesium silicate rocks of the Yoko-Dovyren massif in the production of cement. It is known that this production is material- and energy-intensive. It has a negative impact on the environment, contributing mainly to greenhouse gas emissions into the atmosphere (Shirkhani et al., 2018; Devi et al., 2017; Naqi and Jang, 2019). In addition, sometimes raw materials are located at a great distance from the final production, which requires their replacement with cheaper raw materials, in particular, mining waste (Luo et al., 2016; Sun et al., 2020).

Studies have been carried out on the use of dunites, wehrlites and troctolites of the Yoko-Dovyren massif in the production of Portland cement. Technological regimes have been developed to minimize the consumption of traditional raw materials, replacing them with magnesium silicate rocks. Conditions for obtaining and methods of research are presented in previously published works of the authors (Khudyakova and Voyloshnikov, 2010; Khudyakova et al., 2015). The basic physicochemical and mechanical properties of cements have been studied, the average values of which are presented in Tables 1 and 2.

The obtained values are correlated with the requirements of the Interstate Standard GOST 31108–2016 “Cement for general construction. Technical specifications” and are within the normalized range.

Compared to Portland cement, the obtained materials show increased water and alkali resistance and reduced acid resistance. The compressive strength determined after testing in samples with the addition of magnesium silicate rocks showed higher values than in the control sample. The exception was cements after determination of acid resistance. The data obtained indicate the possibility of using cements with the addition of dunites, wehrlites or troctolites in the construction of facilities in an area with high humidity. In addition, they can be used to work in aggressive environments (alkaline and sulfate). Cement samples are shown in Fig.10.



Fig.10 Cement with the addition of magnesium silicate rocks 300 m above the contact.

Table 1 Physico-mechanical properties of cements with the addition of magnesium silicate rocks.

Parameters	GOST 31108–2016	Cement with the addition of		
		dunite	wehrlite	troctolite
Initial setting time, min.	not earlier than 75	250	255	240
Compressive strength, MPa, age	at least 16.0	21.4	20.5	22.7
	7 days	43.0	42.4	42.9
	28 days	no more than 52.5		
Uniformity of volume change (expansion), mm	no more than 10	5.4	6.1	6.9

Table 2 Physico-chemical properties of cements with the addition of magnesium silicate rocks.

Properties	Cement with the addition of			CEM I
	dunite	wehrlite	troctolite	
Water absorption, %	3.31	3.35	3.61	6.65
Alkali resistance, %	0.93	0.91	0.89	0.69
Acid resistance, %	42.17	41.38	43.96	59.37
Frost resistance, cycle	50	50	50	50

Replacing thirty percent of clinker with dunites, wehrlites and troctolites at the grinding stage in cement production contributes to the saving of traditionally used mineral resources. At the same time, when obtaining one ton of clinker, about 0.58 ton of natural raw materials are saved, of which 0.47 ton of carbonate and 0.11 ton of clay.

In addition, the use of magnesium silicate rocks instead of Portland cement clinker leads to a reduction in the negative impact of cement production on the environment by reducing the emission of carbon dioxide and dust, and reducing energy consumption. All this helps to reduce the cost of commercial products.

3.2 Concrete production

Dunites, wehrlites and troctolites of the Yoko-Dovyren massif can be used as aggregates in the production of concrete. The conducted research provided for establishing the suitability of crushed stone from them for use as a large aggregate. The tests were carried out in accordance with the Interstate Standards of Russia GOST 8267–93 “Crushed stone and gravel from dense rocks for construction work. Technical specifications” and GOST 8269.0–97 “Crushed stone and gravel from dense rocks and industrial wastes for construction work. Methods of physico-mechanical tests”. The results obtained are presented in

Table 3.

No hazardous components and impurities were detected in the studied objects. Poor rock grains were also not found in them. They belong to the crushed stone group I, which allows for the content of platy and needle-shaped grains not exceeding 10 wt.%. The rocks have a high grade for crushing and abrasion capacity. The obtained crushed stone is not affected by the environment. It is not subject to chemical effects of alkalis, and is also resistant to all types of decay. In general, crushed stone complies with the regulated requirements of technical documentation and can be used as aggregate of concrete, as well as for road and other types of construction work.

Dunite sand of the Yoko-Dovyren massif can be used as fine aggregate in the production of concrete. To determine its quality, the authors conducted tests regulated by the Interstate Standards of Russia GOST 8736–2014 “Sand for construction work. Technical specifications” and GOST 8735 – 88 “Sand for construction work. Test methods”. The results obtained, correlated with the requirements of GOST for class II coarse sand, are presented in Table 4.

No hazardous components or impurities were found in the dunite sand. It also does not contain organic or foreign contaminating impurities. The sand can be used for all types of construction work.

Table 3 Physico-mechanical properties of crushed stone from magnesium silicate rocks.

Parameters	Dunite	Wehrlite	Troctolite	GOST 8267–93
Fraction content D_{min} , %	97.80	97.60	98.40	from 90 to 100
Fraction content D_{Max} , %	3.10	3.10	2.90	up to 10
Fraction content 0.5 ($D_{min} + D_{max}$), %	50.45	50.35	50.65	from 30 to 80
Fraction content 1.25 D_{Max} , %	0.18	0.21	0.27	up to 0.5
Content of platy (flaky) and needle-shaped grains, %	no	no	no	no more than 50
Content of poor rock grains, %	no	no	no	no more than 5
Content of dustlike and clay particles, %	0.7	0.7	0.8	no more than 1
Content of clay in lumps, %	no	no	no	no more than 0.25
Mass loss during decay, %	1.00	1.00	1.20	no more than 3
Volumetric bulk weight of crushed stone, $kg \cdot m^{-3}$	1745	1739	1728	
Real density (specific gravity), $g \cdot cm^{-3}$	3.00	3.01	2.91	
Moisture content of crushed stone, %	0.50	0.50	0.50	
Crushed stone grade by crushing capacity	1200	1200	1200	

Table 4 Characteristics of dunite sand of the Yoko-Dovyren massif.

Parameters	Dunite sand	GOST 8267-93
Total residue on the sieve N 063	68.4	from 65 to 75
Modulus of fineness M_f	2.7	from 2.5 to 3.0
Content of grains of size more than 10 mm, %	no	no more than 5
Content of grains of size more than 5 mm, %	no	no more than 20
Content of grains of size less than 0.16 mm, %	4.8	no more than 10
Content of dustlike and clay particles, %	3.0	no more than 3
Content of clay in lumps, %	0.45	no more than 0.5
Specific gravity (real density), $\text{kg} \cdot \text{m}^{-3}$	3000	
Bulk mass (density in the loose-bulk state), $\text{kg} \cdot \text{m}^{-3}$	1900	

Table 5 Physico-mechanical properties of concrete, depending on the type of aggregates.

Type of coarse aggregate	Type of fine aggregate	Compressive strength, MPa	Density, kg/m^3
Dunite	Quartz sand	28.8	2730
	Dunite sand	32.8	2800
Wehrlite	Quartz sand	28.3	2716
	Dunite sand	32.0	2763
Troctolite	Quartz sand	28.0	2613
	Dunite sand	31.5	2666
Granite	Quartz sand	27.3	2297
	Dunite sand	28.4	2358
Gravel	Quartz sand	26.2	2494
	Dunite sand	27.8	2544

The authors studied the effect of crushed stone and sand from magnesium silicate rocks on the technological properties of concrete mixtures (Khudyakova et al., 2014), including compressive strength and density. The obtained parameters of concrete after 28 days of hardening in normal humidity conditions are presented in Table 5. As a comparison, samples containing traditionally used aggregates were produced: granite crushed stone, gravel and quartz-feldspar sand.

It has been established that magnesium silicate rocks have a positive effect on the physico-mechanical properties of concretes, increasing their strength and density. Moreover, samples using crushed stone and sand from dunites as aggregates demonstrated the best results. Depending on the aggregates used, two types of concrete can be obtained: heavy with an average density of up to $2500 \text{ kg} \cdot \text{m}^{-3}$ and extra heavy with an average density of over $2500 \text{ kg} \cdot \text{m}^{-3}$. This allows using the obtained materials both for the production of bearing and special structures. Concrete samples are shown in Fig.11.



Fig.11 Samples of concrete based on magnesium silicate rocks of the Yoko-Dovyren massif.

The use of dunites, wehrlites, troctolites in the production of concrete allows replacing the traditionally used mineral resources. Thus, obtaining 1 m^3 of concrete saves 1565 kg of granite crushed stone or gravel and 457 kg of quartz sand. In addition, this solution is also cost-effective, especially for subsoil users. The development of any field implies the construction of infrastructure fa-

cilities, which requires concrete. Using local raw materials will allow obtaining the necessary material with minimal investment.

3.3 Production of structural ceramics

Magnesium silicate rocks of the Yoko-Dovyren massif can be used to obtain structural ceramics. It is known that the manufacture of ceramic products consumes large volumes of clay raw materials. Their stocks are gradually reduced, and manufacturers are forced to seek an alternative replacement for high-quality clays. Therefore, studies were conducted to establish the possibility of using dunites, wehrlites and troctolites in the production of ceramic bricks.

Magnesium silicate rocks were used as an additive to clay raw materials (Khudyakova et al., 2012; Khudyakova et al., 2018). Products were made in two ways: by plastic molding and semi-dry pressing under a pressure of 40 MPa. The content of rocks in the batch varied from 10 to 50%. The temperature increased in increments of 50 °C from 950 °C to 1100 °C.

As a result of the studies, it was found that the physico-mechanical parameters of ceramic samples are influenced by the type of rock, its amount and firing temperature. The quality of the samples was evaluated according to the Interstate Standard of Russia GOST 530–2012 “Ceramic brick and stone. General technical specifications”. The firing temperature significantly affects the quality of the ceramic crock, the best performance of which is observed at 1100 °C. With an increase in the amount of additives, their values decrease. Samples with the addition

of troctolite demonstrated the worst results, which is explained by the composition of the rock. Compared to dunite and wehrlite, troctolite contains more aluminum and calcium oxides and less magnesium. It also contains a lower percentage of olivine.

The results obtained for ceramic samples containing 40% magnesium-containing rock and calcined at a temperature of 1100 °C are presented in Table 6.

Firing shrinkage and water absorption of ceramic samples decreases with increasing percentage of additives. This is due to the replacement of clay minerals with anhydrous magnesium and iron silicates, which are part of magnesium silicate rocks. Moreover, for samples with the addition of troctolite, these parameters worsen due to the fact that troctolite contains up to 65% olivine. In wehrlite it reaches 85%, and in dunite up to 97%.

The type of rock does not affect the construction and technical properties of ceramic samples. They depend only on the firing temperature. The higher the temperature, the better the properties. For example, after firing at a temperature of 1000 °C, the samples withstand 15 freeze-thawing cycles; at 1050 °C, 30 cycles; and at 1100 °C, more than 150 cycles. The thermal resistance is 15, 25 and 35 cycles, respectively.

In general, ceramic specimens with the addition of magnesium silicate rocks meet the requirements of GOST 530–2012 in their technical characteristics and can be used in construction. Ceramic samples from magnesium silicate rocks of the Yoko-Dovyren massif are presented in Fig.12.

Table 6 Physico-mechanical properties of ceramic samples with the addition of magnesium silicate rocks.

Type of additive	Molding method	Average density, kg · m ⁻³	Firing shrinkage, %	Water absorption, %	Tensile strength, MPa	
					Compression	Bending
No	Plastic	2250	15.7	10.9	65.1	7.5
	Pressing	2280	15.0	9.8	81.6	9.5
Dunite	Plastic	2120	6.8	8.7	31.4	4.3
	Pressing	2630	3.5	6.1	52.3	6.3
Wehrlite	Plastic	2180	7.8	8.7	30.2	4.2
	Pressing	2620	3.8	6.4	49.4	6.2
Troctolite	Plastic	1880	9.2	9.2	28.1	4.2
	Pressing	2620	4.1	6.7	32.1	4.6

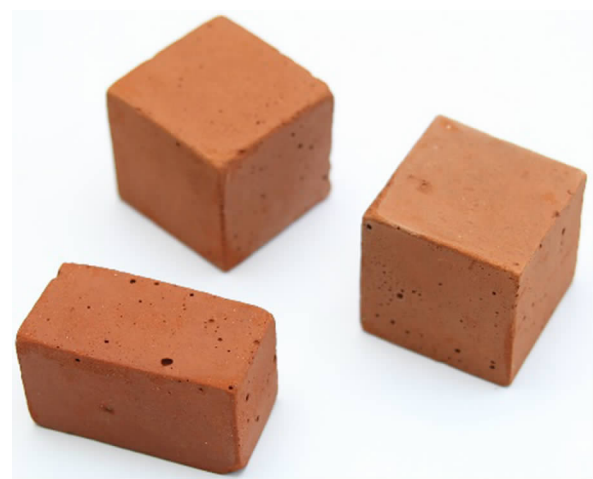


Fig.12 Ceramic brick with the addition of magnesium silicate rocks.

The optimal composition, production parameters and area of use of structural ceramics with the addition of dunites, wehrlites and troctolites are presented in Table 7. The consumption of raw materials is calculated based on the sizes of a single brick 250 mm×120 mm×65 mm specified in GOST 530–2012.

Thus, dunites, wehrlites and troctolites are promising for use as additives in the manufacture of structural ceramics. With a plastic molding method, they can replace up to 40% clay, and with semi-dry pressing up to 100% by obtaining ceramic materials directly from the rocks themselves. Moreover, the amount of saved clay in the production of 1000 bricks in the first case will be 1529 kg, and in the second 5148 kg. The involve-

ment of magnesium silicate rocks in the process of production of ceramic materials will reduce the use of traditionally used mineral raw materials.

3.4 Production of asphalt concrete

Magnesium silicate rocks contain a large number of calcium, magnesium and iron cations and can be used as a mineral powder in the manufacture of asphalt concrete mixtures. This component plays an important role, because, combined with bitumen, it forms the microstructure of asphalt concrete.

Studies have been carried out to obtain mineral powders from dunites, wehrlites, troctolites and to establish their quality in accordance with the requirements of the State Standard of the Russian Federation, GOST R 52129–2003 “Mineral powder for asphalt concrete and organomineral mixtures. Technical specifications” (Khudyakova and Voiloshnikov, 2017). It has been established that the type of powder and its specific surface area influence the adsorption activity with respect to bitumen. With an increase in the specific surface area, the number of active centers capable of sorbing bitumen increases, forming a structured dispersion system. The powder from dunite turned out to be the most active followed by the powder from troctolite. They surpass traditionally used limestone mineral powder in quality. Wehrlite showed the worst adsorption values.

The characteristics of the obtained materials have been studied. The results are presented in Table 8.

Table 7 Optimal composition, production parameters and area of use of ceramic bricks.

Raw materials	Unit	Material consumption per 1000 bricks	Processing type and parameters	Area of use
Clay	kg	2293.2	Plastic molding, firing at 1050 °C and higher	For laying and cladding of external and internal walls of buildings and structures, as well as for laying of foundations
Magnesium silicate rocks	kg	1528.8		
Water	l	764.4		
Clay	kg	2574.0	Pressing with a pressure of 40 MPa, firing at 950–1100 °C	For laying and cladding of external and internal walls of buildings and structures
Magnesium silicate rocks	kg	2574.0		
Water	l	411.8		

Table 8 Physico-mechanical properties of mineral powder from magnesium silicate rocks.

Parameters	Mineral powder from			Requirements of GOST R 52129–2003
	dunite	wehrlite	troctolite	
Porosity, %	30.6	30.7	31.2	no more than 40
Swelling of samples from a mixture of powder with bitumen	0	0	0	no more than 3.0
Water resistance of samples from a mixture of powder and bitumen	0.2	0.2	0.3	no more than 0.7
Humidity, % by weight	2.0	1.8	2.1	no more than 2.5
Real density, kg · m ^{−3}	3330	3340	3240	

the development of mineral deposits. Involving non-demanded resources in the production turnover will prevent them from getting into dumps, thereby solving the issues of geocological safety of mining production.

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